Knapp

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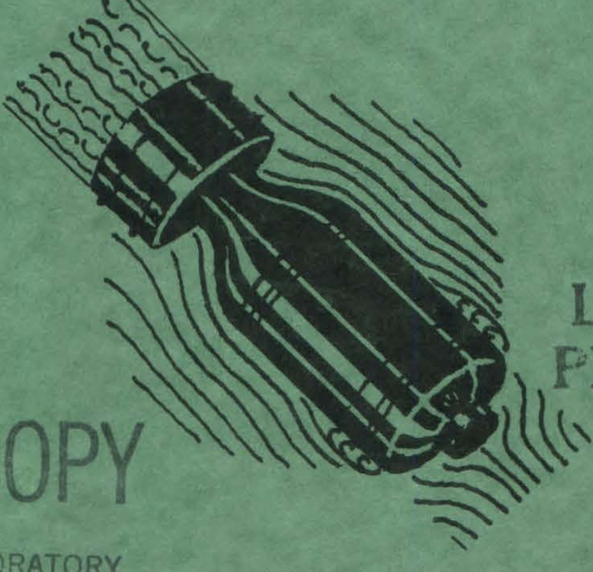
ND-14

WATER TUNNEL TESTS
OF THE
AN-MK. 41 BOMB.



ND 14

THE HIGH SPEED WATER TUNNEL
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA.

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Office of Scientific Research and Development

National Defense Research Committee

Division Six - Section 6.1

MEMORANDUM ON WATER TUNNEL TESTS OF THE AN-MK. 41 BOMB

(Laboratory Designation ND-14)

by

Robert T. Knapp
Official Investigator

The High Speed Water Tunnel
at the
California Institute of Technology
Hydraulic Machinery Laboratory
Pasadena, Caliifornia

March 31, 1943

HML Rep. No. ND-14
Copy No. 69

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ABSTRACT

The High Speed Water Tunnel is operated by the California Institute of Technology under Contract OEMsr-207 with the OSRD and is sponsored by Division 6, Section 6.1 of the NDRC. The tests reported in this memorandum were made at the request of the U. S. Navy Department, Bureau of Ordnance as a part of Navy Project ND-141.

The report covers water tunnel tests of a 2" diameter model of the 15" AN-MK. 41 Bomb (Model Scale Ratio 7.5 to 1), and several modifications of this bomb. The hydrodynamic forces, the drag, crosswind force, and the moment, acting on the projectiles were measured and the locations of the center-of-pressure were calculated for various velocities and yaw angles.

The Summary, given on page 13, reports the following main findings:

(1) For the standard MK. 41 Bomb the measured drag is high. The performance curves show discontinuities or "jumps" in behavior as the yaw angle changes, resulting in lower drag and less stability at angles above 6 degrees.

(2) If the nose is modified slightly the drag is reduced by 40% and the discontinuities in performance are eliminated. However, with this nose the stability is reduced at all yaw angles.

(3) Using a different tail and afterbody with the modified nose, an additional reduction in drag is effected and good stability is maintained at all yaw angles without the recurrence of the discontinuities. The reduction in drag with this combination is sufficient to increase the terminal fall velocity of the bomb in water from about 15 feet per second to about 23 feet per second.

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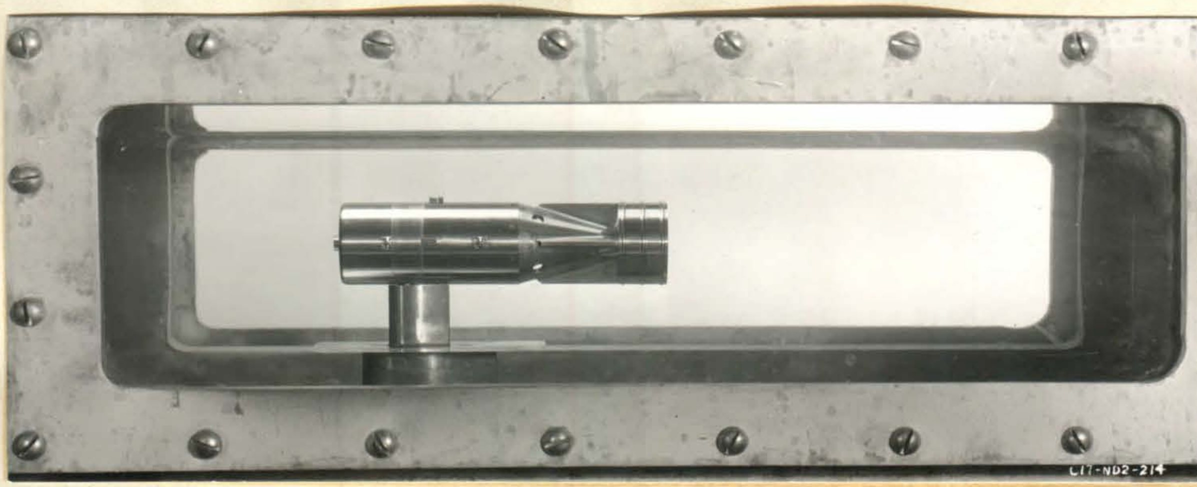

Figure 1. 2" Diameter Model of the AN Mk. 41 Bomb Shown Mounted in the Water Tunnel Working Section.

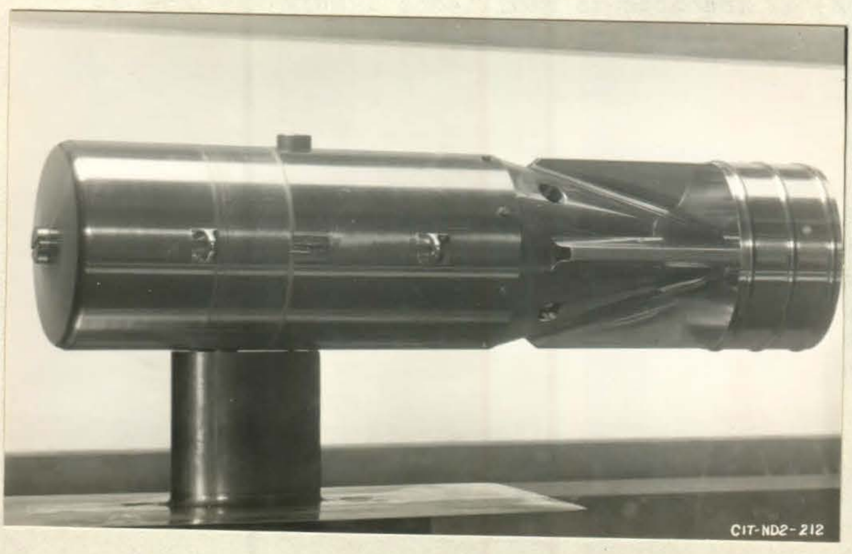

Figure 2. Closeup View of Mk. 41 Bomb in Water Tunnel Working Section.

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MEMORANDUM OF WATER TUNNEL TESTS OF THE AN-MK. 41 BOMB

(Laboratory Designation, ND-14)

1. Type of Projectile and Purpose of Tests.

This report covers water tunnel tests of a 2" diameter model of the 15" AN-Mk.41 Bomb (designation in the laboratory as projectile number ND-14). The purpose of the tests was to determine the magnitude of the hydrodynamic forces acting on the projectile as functions of its orientation with respect to the direction of motion, and to determine the location of the point of application of those forces.

2. Tunnel Installation and Description of Forces Measured.

The tests were conducted in the 14" diameter working section of the High speed Water Tunnel at the California Institute of Technology(1) Figure 1 shows the projectile installed in the tunnel. In order to reduce the drag tare to a minimum, the rigid supporting spindle is protected from the flow by the streamline shielding shown in the figure. This shielding which projects to within a few thousandths of an inch of the projectile is held to a small size in order to reduce interference effects.

The forces exerted by the flow on the model can be resolved, in general, into a drag force parallel to the flow, a cross wind force normal to the flow and a moment or torque acting about the point of support. These are the forces measured during the tests. The moment exists only if the model is not supported at the point of application of the resultant of all the hydrodynamic forces. It is clear that the magnitude and sense of the measured moment will change if the point of support is shifted along the body.

The data presented in this report have not been corrected for scale effect, tare or interference of the model support. However, the results are believed to be close to the correct values. Similar tunnel tests of streamlined projectiles have given data that agree closely with those obtained from full scale field tests.

3. Representation of Test Data.

The hydrodynamic characteristics are presented in the form of curves of force coefficients as functions of the angle of yaw. In addition, the distance of the center-of-pressure from the nose of the projectile expressed as a fraction of the length of the projectile is plotted against yaw angle. The center-of-pressure is defined as the point at which the resultant hydrodynamic force vector intersects the axis of symmetry of the model.

(1) Figures refer to references listed at the end of this report.

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The force coefficients, C_D, for drag, and C_C, for cross wind force are expressed as:

$$C_D = \frac{D}{\rho \frac{V^2}{2} A_D}$$

and

$$C_C = \frac{C}{\rho \frac{V^2}{2} A_D}$$

where

D = measured drag force in lbs

C = measured cross wind force in lbs

ρ = density of water in slugs per cu ft

A_D = area in sq ft of a cross section at the cylindrical portion of the projectile taken normal to the geometric axis of the projectile

V = mean relative velocity between the water and the projectile in ft per sec

The moment coefficient is expressed as:

$$C_M = \frac{M}{\rho \frac{V^2}{2} A_D L}$$

where

M = moment in in-lbs measured about any particular point on the geometric axis of the projectile

L = overall length of the projectile in in. (For all combinations of the model projectile discussed in this report L is taken as 6.80").

The distance from the nose of the center-of-pressure (center-of-pressure distance) as a fraction of the overall projectile length is expressed as:

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$$\frac{\bar{x}}{L} = \frac{L' + L''}{L} = \frac{L'}{L} + \frac{M}{L(C\cos\psi + D\sin\psi}$$

where

L' = distance in in from the projectile nose to the center of moments

L'' = distance in in from the center-of-pressure to the center of moments

ψ = yaw angle in degrees

When M is the measured moment the center of moments is at the support point of the model and L'' then is the distance from the support point to the center-of-pressure. The signs of the moment, M, the cross wind force, C, and the yaw angle, ψ, are such that a positive or clockwise moment will tend to increase a positive or clockwise yaw angle, while the corresponding positive cross wind force will act in the same direction as the displacement of the projectile nose for a positive yaw.

The curves of force and moment coefficients and of center-of-pressure distance plotted as functions of the yaw angle are useful for a discussion of the stability of projectiles. Since these tunnel tests are made under steady flow conditions the results will only indicate the tendency of the projectile to return to or move away from the equilibrium position after a disturbance. Adopting aerodynamic usage a projectile is said to be "statically" stable if it tends to return to equilibrium when disturbed. In the discussion of static stability the actual motion following the perturbation is not considered at all. In fact, a projectile may oscillate about the equilibrium position without ever remaining in it. In this case the projectile would be statically stable even though "dynamically" unstable. For a complete discussion of the mode of motion to be expected following a perturbation, the "dynamic" stability, additional information is necessary.

The condition for equilibrium is satisfied if C_M calculated about the C.G. is equal to zero. In general, for projectiles with axial symmetry the moment is zero at $\psi = 0^\circ$ so that for equilibrium the projectile is oriented with its axis parallel to the direction of motion. If the projectile is rotated from the equilibrium position so as to give it a positive yaw angle it is necessary that it have a negative coefficient, according to the sign convention adopted, in order that it be statically stable. Thus a negative slope of the curve C_M vs. ψ corresponds to static stability, and a positive slope corresponds to instability. The degree of stability or instability is measured by the magnitude of the slope. The same conclusions are obtained by interpreting the center-

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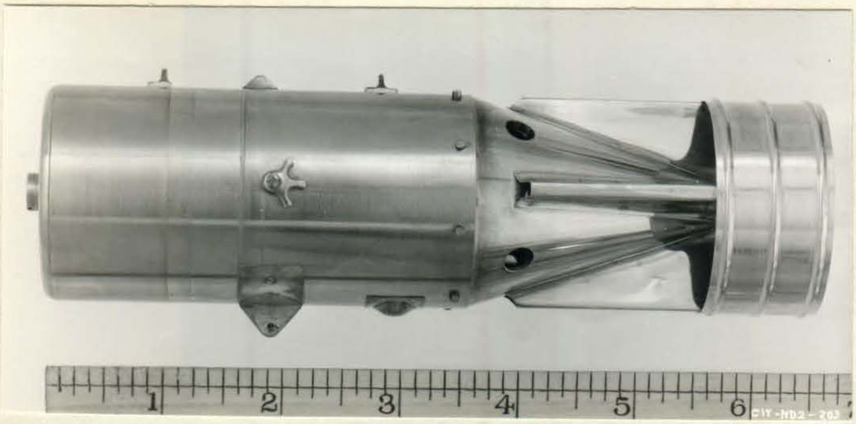

Figure 3.

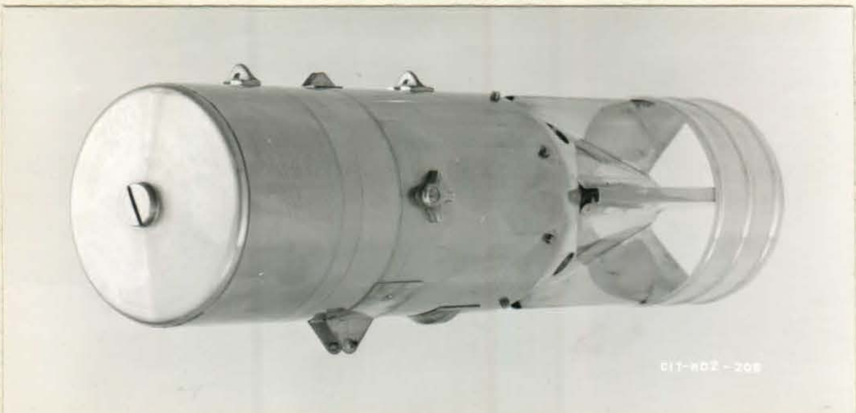

Figure 4.

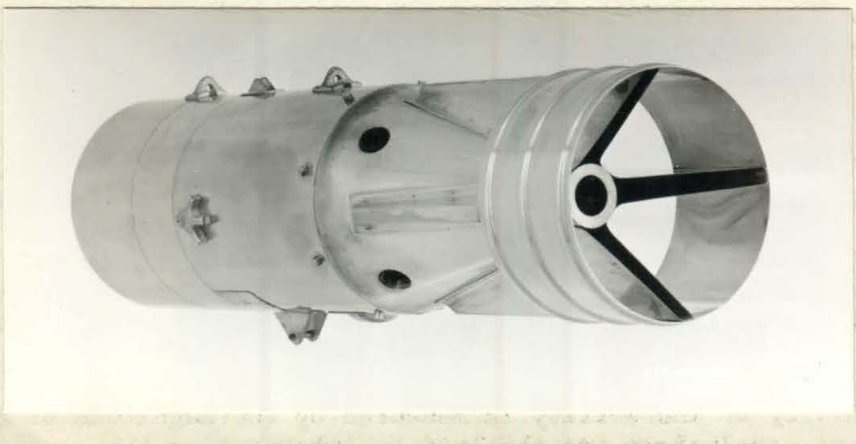

Figure 5.

2" Diameter Model of the AN Mk. 41 Bomb.

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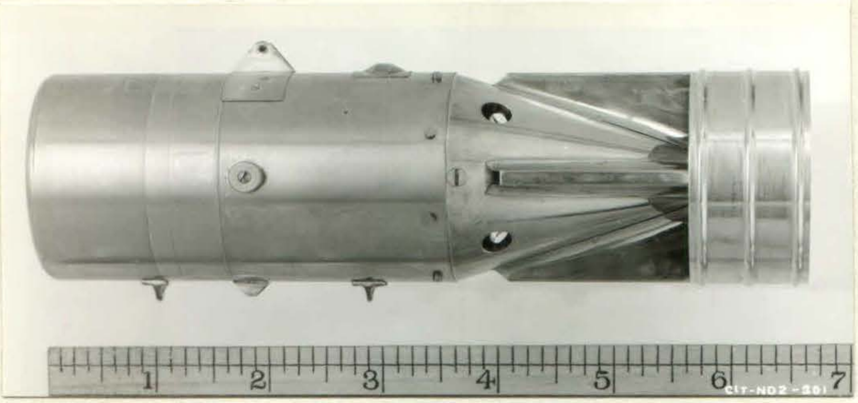

Figure 6.
Suspension Bracket and Fork Rest at Top.

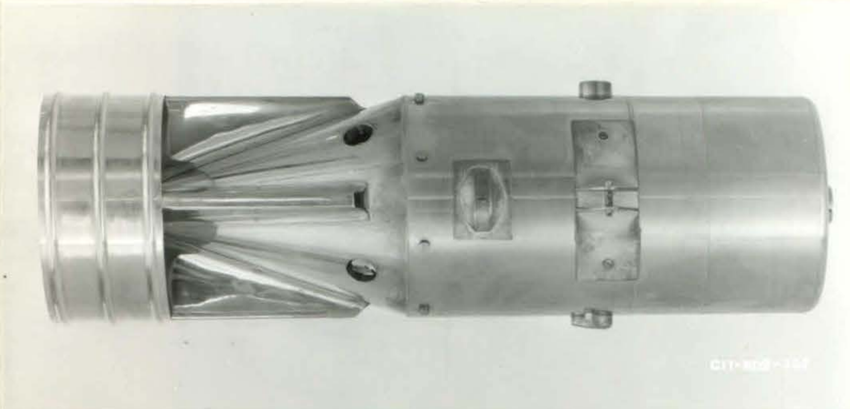

Figure 7.
View Showing Suspension Bracket and Fork Rest.

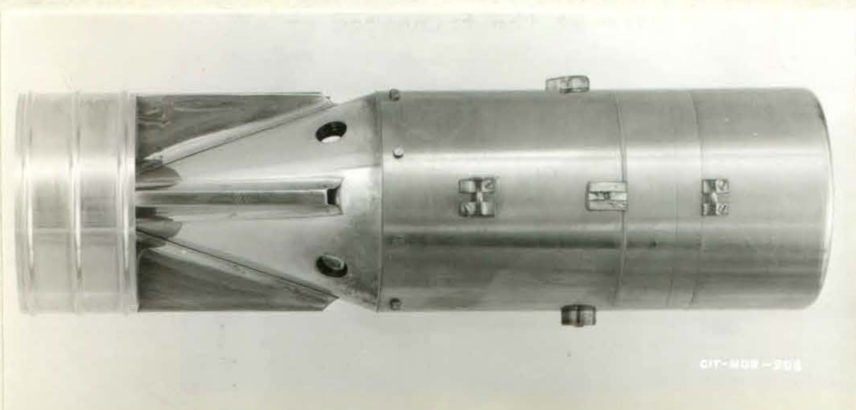

Figure 8.
View Showing Suspension Lugs and Hoisting Lug.

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of-pressure curves. For symmetrical projectiles, if the center-of-pressure falls behind the center-of-gravity a negative or restoring moment exists and the projectile is statically stable. If the C·P. lies ahead of the C.G. the moment is non-restoring and the projectile is statically unstable. The degree of stability or instability is measured by the distance between the center-of-gravity and center-of-pressure.

4. Description of Projectile Model and Technique of Installation in Tunnel.

A 2" diameter model of the 15" AN-Mk. 41 Bomb was used for the water tunnel tests. The model was constructed to scale from United States Navy Bureau of Ordnance drawings 329670, 329671, 329672, 329674, 329675, 329676, 329677, 329678, and 329679. The model is complete in all details except for the nose fuse and arming propeller. The proportions of the projectile and the general arrangement of its component parts are shown on the assembly drawing of Figure 15. It will be noted that several fittings project from the cylindrical body section of the projectile. These hoisting and suspension lugs, fuse covers, and the resting device are shown also in the photographs of the model details given in Figures 3 to 8, inclusive. The nose of the model bomb is equipped with a solid boss which represents the nose fuse of the full size projectile. The small arming propeller which is mounted on a shaft projecting from the nose fuse on the prototype bomb is not included on the model. The nose of the bomb is very flat, and as the detail drawing in Figure 16 shows, the radius of curvature at the junction between the nose and the cylindrical body is small. In addition on the full scale bomb the nose is lap welded to the body section leaving a step in the profile at the junction point. A welding bead is laid along this step in the prototype. The step is shown in Figure 15 and can be seen as it appears on the model in Figures 3 and 6. The afterbody is fastened to the cylinder by eight machine screws whose heads are seen in the photographs of the model. The prototype afterbody is a hollow truncated cone of light sheet metal construction which is vented by four holes spaced at 90° around the circumference near the large or forward end of the cone and by the opening at the truncated or aft end. The model afterbody and tail construction details are given in Figure 17 and detail pictures of the completed piece are shown in Figures 9 and 10. The tail is made of a cylindrical shroud ring supported by four sets of fins so its axis coincides with the axis of the projectile. The tail shroud ring has three circumferential reinforcing ribs. The tail fins are made with two walls set a small distance apart, thus forming a passage which is parallel to and in the plane of the projectile axis and which is open at both ends. This construction is clearly indicated in Figures 9 and 10.

The model is constructed in several sections. This technique, adopted for all water tunnel models, (I) provides flexibility for supporting the projectile and for testing variations of any of the components of the projectile. The sections which make up the Mk. 41 Bomb are shown disassembled in Figure 10. The several pieces are held together by the longitutinal screw shown in the foreground. It is possible to replace any of these model parts with other pieces from the laboratory stock of noses, body and afterbody sections, and tails. Figures 11 and 12 show one such combination which was made up of the Mk. 41 nose with a clean cylindrical body and with another afterbody and another ring tail. These are designated as afterbody No. 3 and tail No. 5. Figures 13 and 14 show another variation where the Mk. 41 nose has been replaced by another nose (Nose No. 2) having a slightly different profile. Details of nose No. 2, afterbody No. 3, and tail No. 5 are shown in Figure 18. These parts were originally designed for other projectiles tested in the laboratory and are available for further use. One additional feature of the Mk. 41 Model is that the special fittings (suspension lugs, etc.) are attached with small screws so as to be readily removable; thus tests are possible with or without fittings.

A 2" diameter "center section" attached to the supporting spindle furnishes a means of mounting the model in the water tunnel working section. This center section forms a portion of the cylindrical body of the model and the remaining forward and aft sections of the model are attached to it by means of a longitutinal screw. Figures 1 and 2 show the Mk. 41 Bomb installed in the tunnel. The vertical supporting spindle which projects from the bottom of the tunnel is shielded from the flow by the streamline shape pictured below the model. The model is yawed in a horizontal plane perpendicular to the page by rotating the spindle. For projectiles, such as this one, which is not completely symmetrical it is desirable to test them in several planes of yaw. The construction of the model makes this possible. By rotating the model parts about the geometric axis of the projectile the effective yaw plane may be varied.

For this particular model the fittings and the spindle shield interfere for some positions of the projectile body. This made it necessary to remove one of the fittings for some tests. Thus for the installation pictured in Figure 2 which shows the suspension lugs facing the reader, the fuse water baffle fitting was removed in order that the model clear the shield. Note that if the bomb hangs from the suspension lugs, a vertical plane passes through them and through the center line of the bomb. The tunnel installation of Figure 2. therefore, corresponds to yaw in the vertical plane. Tests were made with this installation and also with the model rotated 180° about its axis and with the opposite fitting (the cylindrical fuse cap shown at the top in Figure 2) removed instead. In addition to tests in these two positions, measurements were made with the model rotated so the angle between the yaw plane and the vertical plane of the projectile as just defined was 45°. These three positions for supporting the model are indicated graphically in Figure 19.

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Figure 9. View of Tail Showing Double Walled Fins and Ring Shroud. Note that hollow conical afterbody is vented by holes on cone surface and at cone tip.

Figure 10. Parts for 2" Diameter Model of AN Mk. 41 Bomb showing Method of Construction and Assembly.

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Figure 11.

Figure 12.

Bomb assembly using Mk. 41 nose with laboratory body and tail parts (afterbody No. 3 and Tail No. 5).

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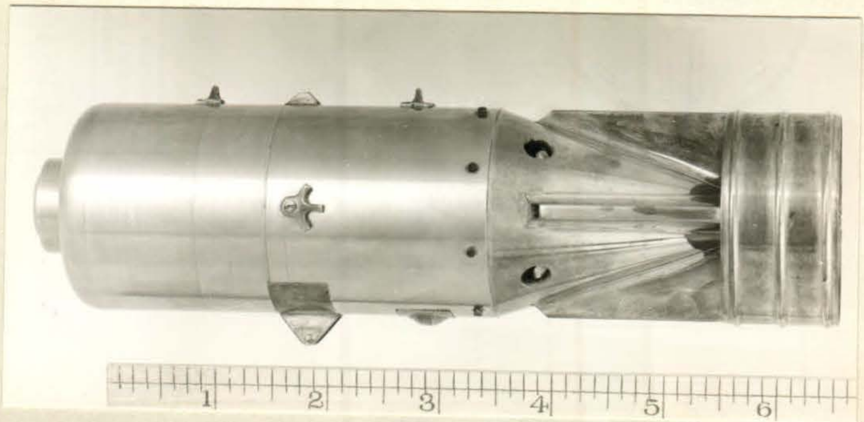

Figure 13.

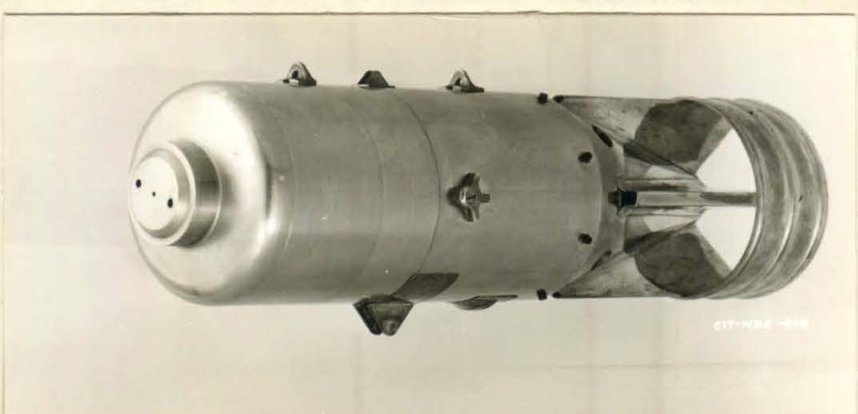

Figure 14.

Mk. 41 Bomb with nose replaced
by laboratory Nose No. 2.

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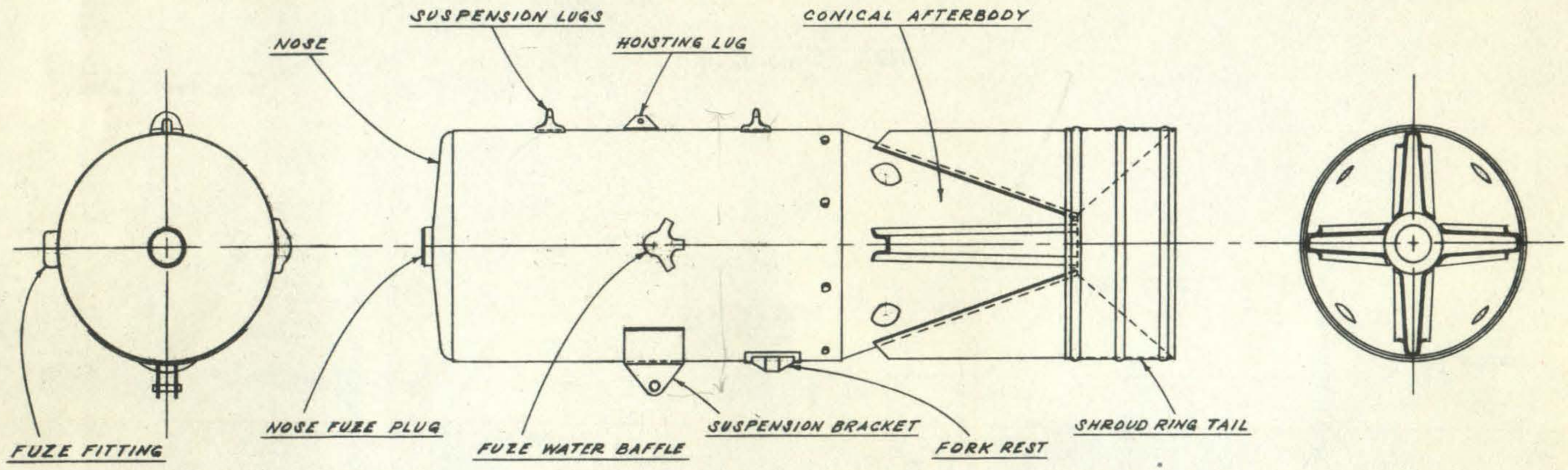

HYDRAULIC MACHINERY LABORATORY CALIFORNIA INSTITUTE OF TECHNOLOGY PASADENA, CALIFORNIA	
AN-MK. 41 BOMB	
DR CRA 2-8-43	SCALE
CH HB	ND-186-16-U
AP JW Daily	

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FIG. 15

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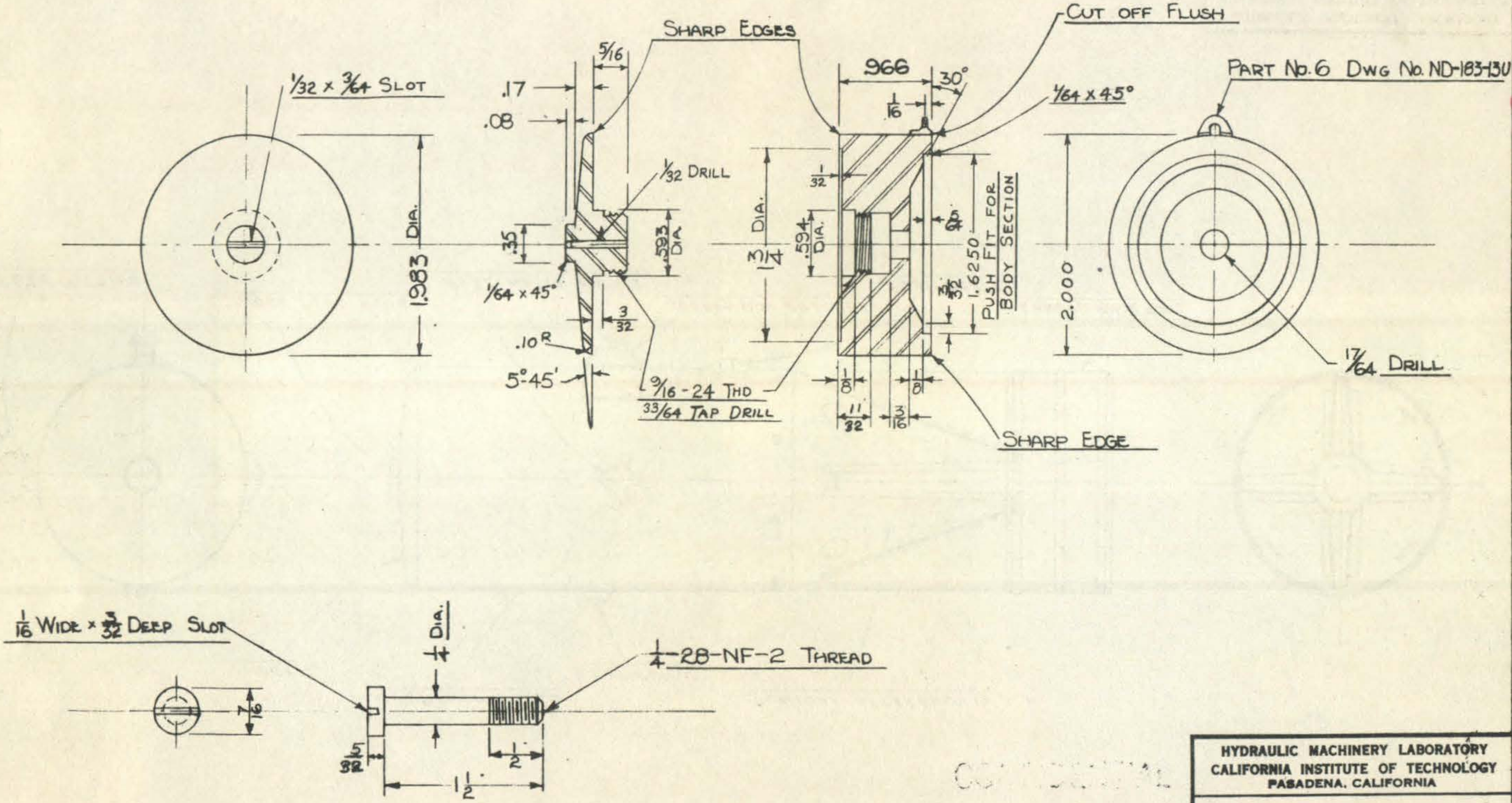

MATERIAL – BETHALON 416

HYDRAULIC MACHINERY LABORATORY
CALIFORNIA INSTITUTE OF TECHNOLOGY
PASADENA, CALIFORNIA

MODEL NOSE No. 28
AN-MK 41 BOMB

DR L.N.N. 2-1-43	SCALE ~ FULL
CH HB	ND-181-28-U
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FIG 16

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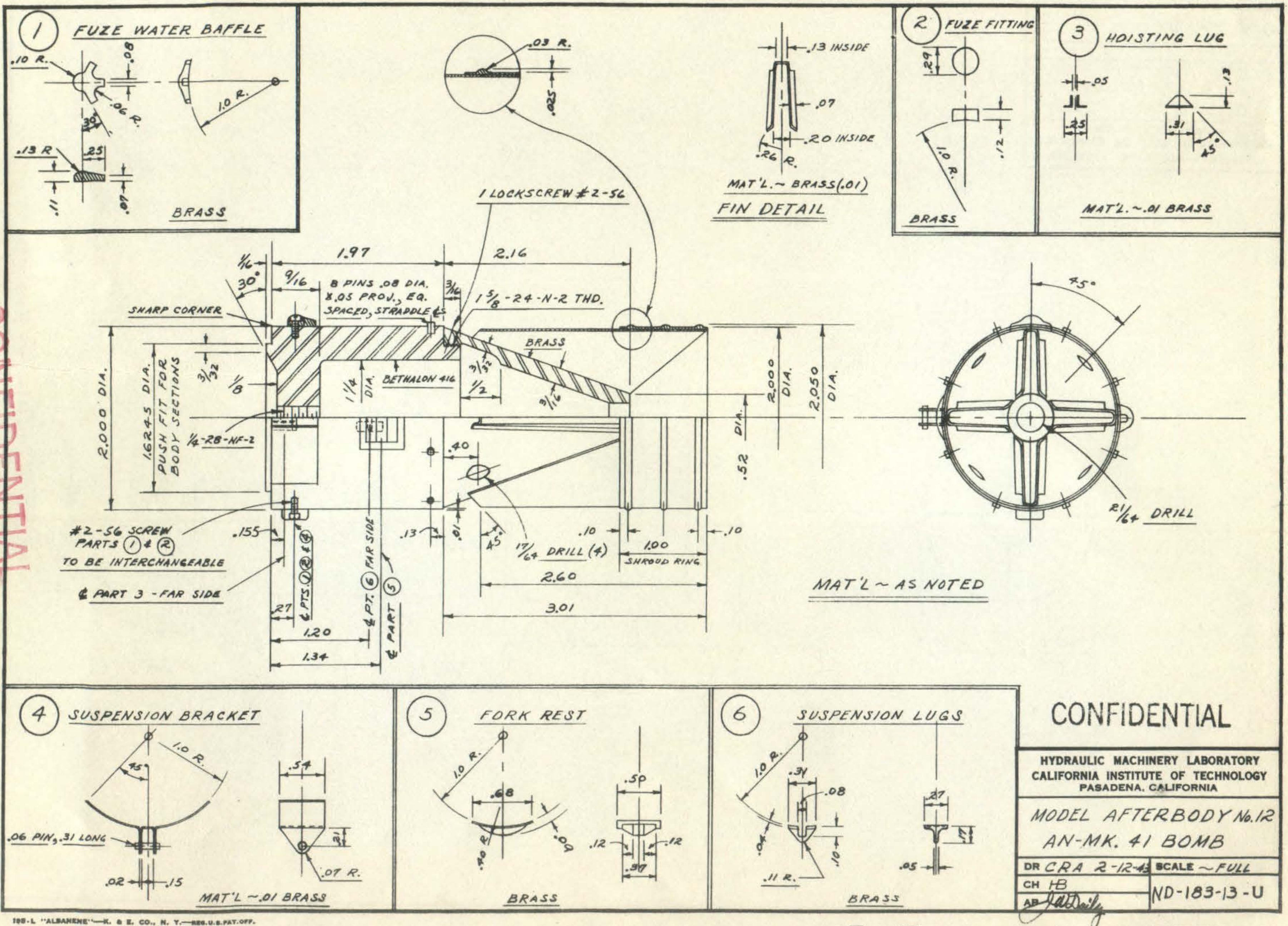

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108-L "ALBANENE"—K. & E. CO., N. Y.—REG.U.S.PAT.OFF.

FIG. 17

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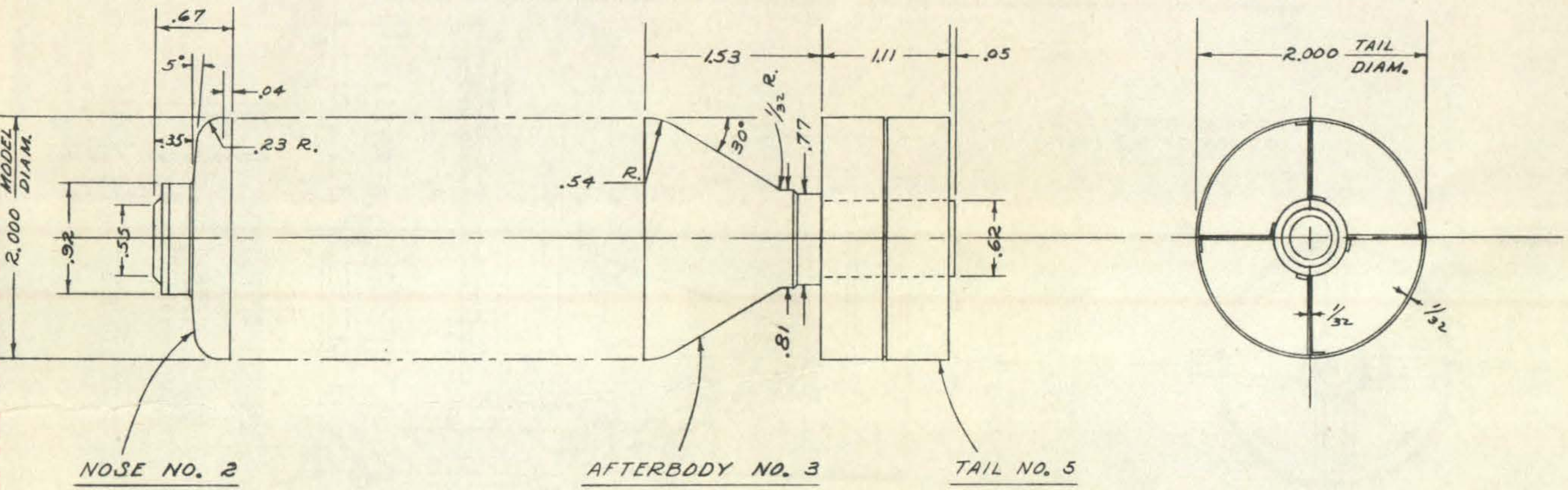

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PASADENA, CALIFORNIA

MODEL PARTS USED IN COMBINATION WITH MK.-41 BOMB PARTS

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FIG. 18

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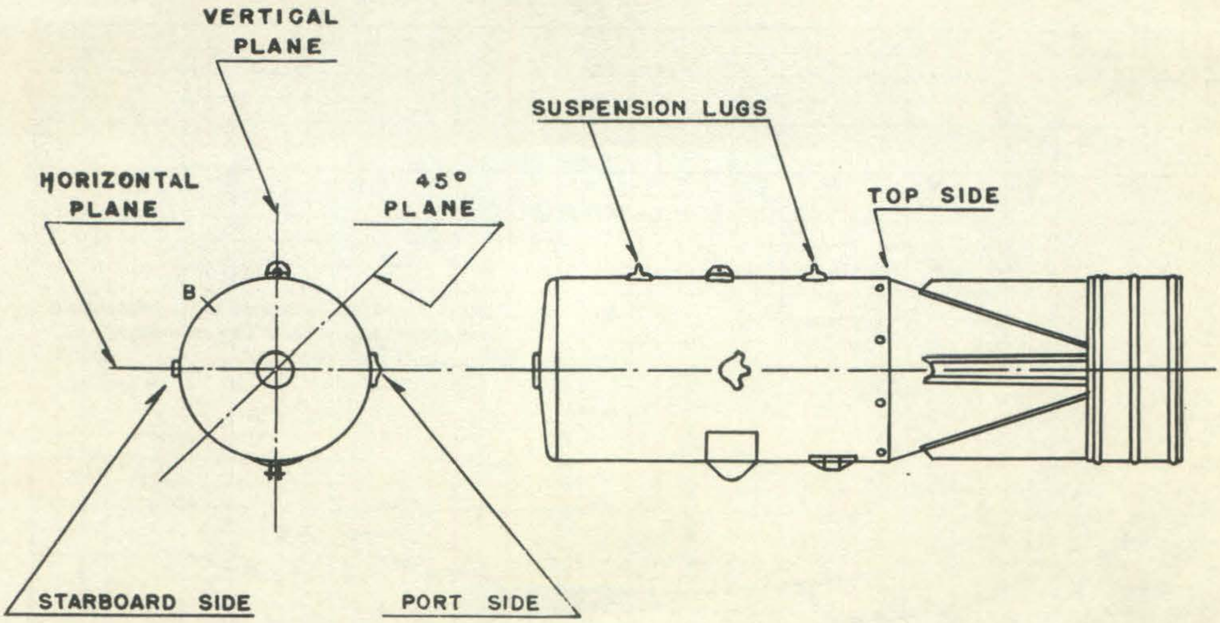

YAW ANGLE POSITIVE IF NOSE TILTED UPWARD WITH RESPECT TO RELATIVE FLOW PAST MODEL

YAW PLANE ORIENTATION AND SUPPORT LOCATION FOR MODEL TESTS

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CH	FIG. 19	ND 14 - 677 L
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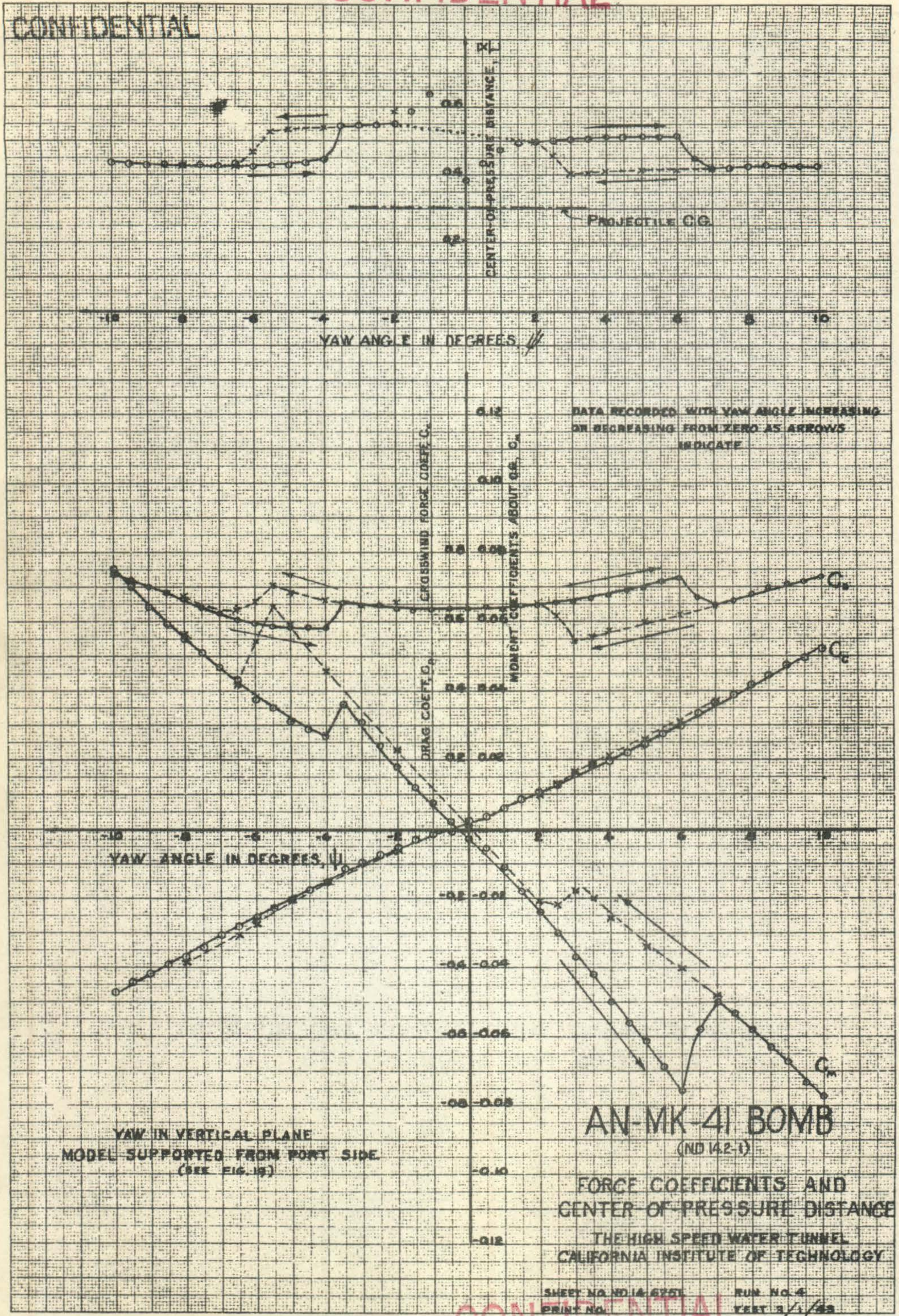
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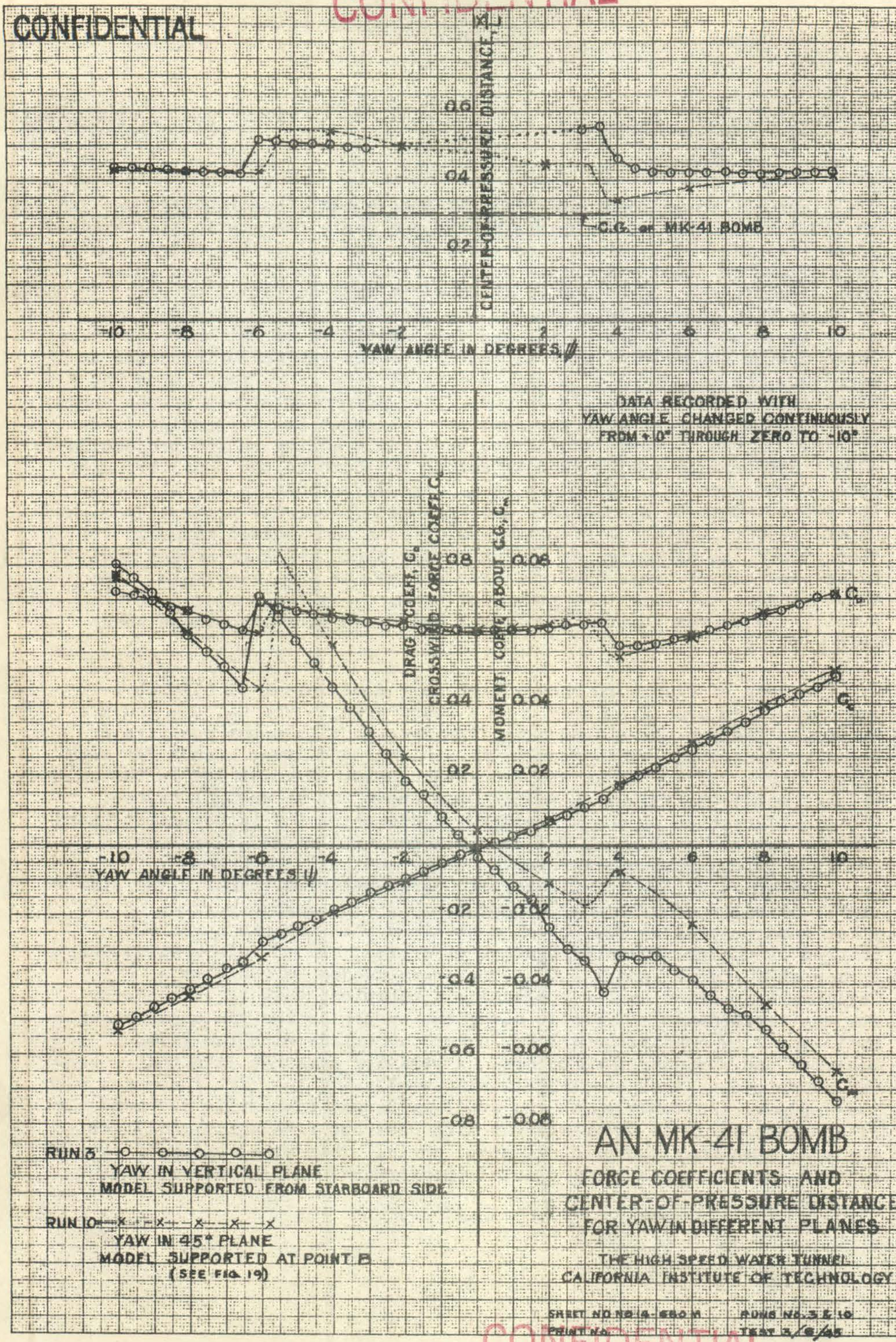
CENTER-OF-PRESSURE DISTANCE
0.6
0.4
0.2
PROJECTILE C.G.
-10
-8
-6
-4
-2
2
4
6
8
10
YAW ANGLE IN DEGREES, ψ
DATA RECORDED WITH YAW ANGLE INCREASING OR DECREASING FROM ZERO AS ARROWS INDICATE
CROSSWIND FORCE COEFF. C_c
MOMENT COEFFICIENTS ABOUT C.G. C_m
DRAG COEFT. C_D
0.12
0.10
0.8 0.08
0.6 0.06
0.4 0.04
0.2 0.02
-0.2 -0.02
-0.4 -0.04
-0.6 -0.06
-0.8 -0.08
-0.10
-0.12
C_D
C_c
C_m
YAW ANGLE IN DEGREES, ψ
YAW IN VERTICAL PLANE
MODEL SUPPORTED FROM PORT SIDE
(SEE FIG. 19)
AN-MK-41 BOMB
(ND 142-1)
FORCE COEFFICIENTS AND
CENTER-OF-PRESSURE DISTANCE
THE HIGH SPEED WATER TUNNEL
CALIFORNIA INSTITUTE OF TECHNOLOGY
SHEET NO. ND 14-6751
PRINT NO.
RUN NO. 4
TEST 3/1/43

FIG 20

5. Test Results - Discussion of Performance Curve and Effects of Projectile Design Features.

Figure 20 shows force coefficients and center pressure distances for the Mk. 41 Bomb plotted as functions of the yaw angle for yaw in the vertical plane (see fig. 19). It will be noted that the calculated values for $\bar{x}/L$ in the zone of small yaw angles deviate from the dotted curves shown. Too much significance should not be attached to this deviation of $\bar{x}/L$. It merely means that because of asymmetry the moment is finite when the cross wind force is zero. This causes the absolute magnitude of $\bar{x}/L$ to become very large and to change sign at this point. As the yaw angle increases in magnitude the condition of finite moment at zero cross wind force has a negligible effect on the $\bar{x}/L$ values. This asymmetry effect on the shape of the $\bar{x}/L$ curve near zero yaw does not mean that the projectile is unstable. As the C_M curve indicates, the couple acting on the projectile is always restoring and will tend to rotate the bomb to the equilibrium or zero moment postion. If there is a large difference in angle between the points where C_C equals zero and C_M equals zero, the projectile might be expected to "side slip" or behave in some complicated manner. For these tests the asymmetry is not extremely large and both moment and cross wind curves cross the axis at close to the same yaw angle. For these reasons the slight asymmetry of the projectile is overlocked in drawing the curves and the $\bar{x}/L$ curves are drawn as smooth lines near zero yaw.

The data of Figure 20 show a high drag coefficient of 0.64 at zero yaw angle. In addition, they show a sharp drop in the C_D, C_M, and $\bar{x}/L$ curves as the yaw angle increases from zero in either the positive or negative direction. This results in a higher and lower branch for each curve with a difference at the transition point of about 15% in the C_D values, about 30% in the C_M values, and about 20% in the $\bar{x}/L$ values. The exact location of the transition or discontinuity is dependent upon how the yaw angle changes. The curves shown with a full line were obtained by changing the yaw angle during the test continuously from large negative values through zero to large positive values. The discontinuities occur at $\psi = -3.5^\circ$ and $+ 6.0^\circ$. The dashed curves, on the other hand, represent the behavior obtained when the yaw angle was changed in the positive to negative direction, and the discontinuities appear at $\psi = -5.5^\circ$ and $+ 3.0^\circ$. The superimposed curves show a "hysteresis" effect in the projectile's behavior, that is, a tendency for the performance to persist along one branch as the yaw angle changes until the flow conditions are no longer compatible with the given behavior and a sudden jump occurs. A behavior somewhat like that observed above occurs when an aircraft wing stalls.(2) The lift increases with the angle of incidence up to the stall angle and then falls off suddenly. If then the angle is decreased the lift does not rise again until the angle is less than the original stall angle. This overlapping of curves gives a zone in which the projectile performance will be uncertain.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CENTER-OF-PRESSURE DISTANCE, X/L
C.G. of MK-41 BOMB
YAW ANGLE IN DEGREES, ψ
DATA RECORDED WITH
YAW ANGLE CHANGED CONTINUOUSLY
FROM +10° THROUGH ZERO TO -10°
DRAG COEFF., C_D
CROSSWIND FORCE COEFF., C_C
MOMENT COEFF. ABOUT C.G., C_M
C_D
C_C
C_M
YAW ANGLE IN DEGREES ψ
RUN 3
YAW IN VERTICAL PLANE
MODEL SUPPORTED FROM STARBOARD SIDE
RUN 10
YAW IN 45° PLANE
MODEL SUPPORTED AT POINT B
(SEE FIG. 19)
AN-MK-41 BOMB
FORCE COEFFICIENTS AND
CENTER-OF-PRESSURE DISTANCE
FOR YAW IN DIFFERENT PLANES
THE HIGH SPEED WATER TUNNEL
CALIFORNIA INSTITUTE OF TECHNOLOGY
RUNS NO. 3 & 10

FIG. 21

The above results are for tests with the model supported on its port side and yawed in a plane corresponding to the vertical for the bomb. (See model orientation diagram in Figure 19). Similar performance curves were obtained when the model was supported on its starboard side and yawed in the same vertical plane, and also when the model was yawed in a plane inclined at 45° to the vertical. These results, shown in Figure 21, also exhibit the tendency for the mode of behavior to persist as the yaw angle is changed. Both sets of data in Figure 21 show the discontinuity to occur at nearly the same yaw angles. The results may be compared since for both runs the yaw angle was changed continuously from large positive values to large negative values. Note, however, that the behavior is only partially indicated and that a complete picture such as given by Figure 20 would require additional runs with the yaw swept in the other direction. The effect of these two methods of supporting the model has only a minor influence on the test results. The moment coefficient curve for yaw in the 45° plane has about the same slope as for yaw in the vertical plane (port side support) but is displaced slightly. This is caused largely by asymmetry in the projectile construction. The center-of-pressure distance shows some deviation as a result of this change in moment, especially for small yaw angles. The drag and the crosswind force coefficients are almost uneffected by the change in support and plane of yaw. Run 3 of Figure 21 may be compared with the dashed curves in Figure 20 for the port side support. These two tests made with the model yawed in the vertical plane give almost the same results. The drag is slightly lower ($C_D = 0.61$) when the model is supported on its starboard side, but the other characteristics are unchanged.

The discontinuous behavior of the coefficient curves is an indication that the flow regime about the model changes suddenly. An examination of the model drawings in Figures 15, 16, and 17 and reference to the photograph in Figure 3 will show that there are three possible features of the projectile's construction which might influence the flow enough to cause such a change. One of these is the suspension fittings (lugs, etc.) which are attached to the surface of the projectile. Another lies in the construction of the afterbody and tail. In particular, it will be noticed that the junction is abrupt where the conical afterbody is attached to the cylindrical portion of the projectile. The third feature is the nose construction. As the photograph of the bomb projectile in Figure 3 and the detail drawing in Figure 16 clearly show the flat nose is joined to the cylindrical projectile body by means of a very short radius curve. In addition, there is a small step in the projectile at the junction which represents the overlapping of the cylindrical body shell on to the nose in the prototype construction.

In order to isolate the effects of each of these features a series of tests was made with the following combinations of model parts.

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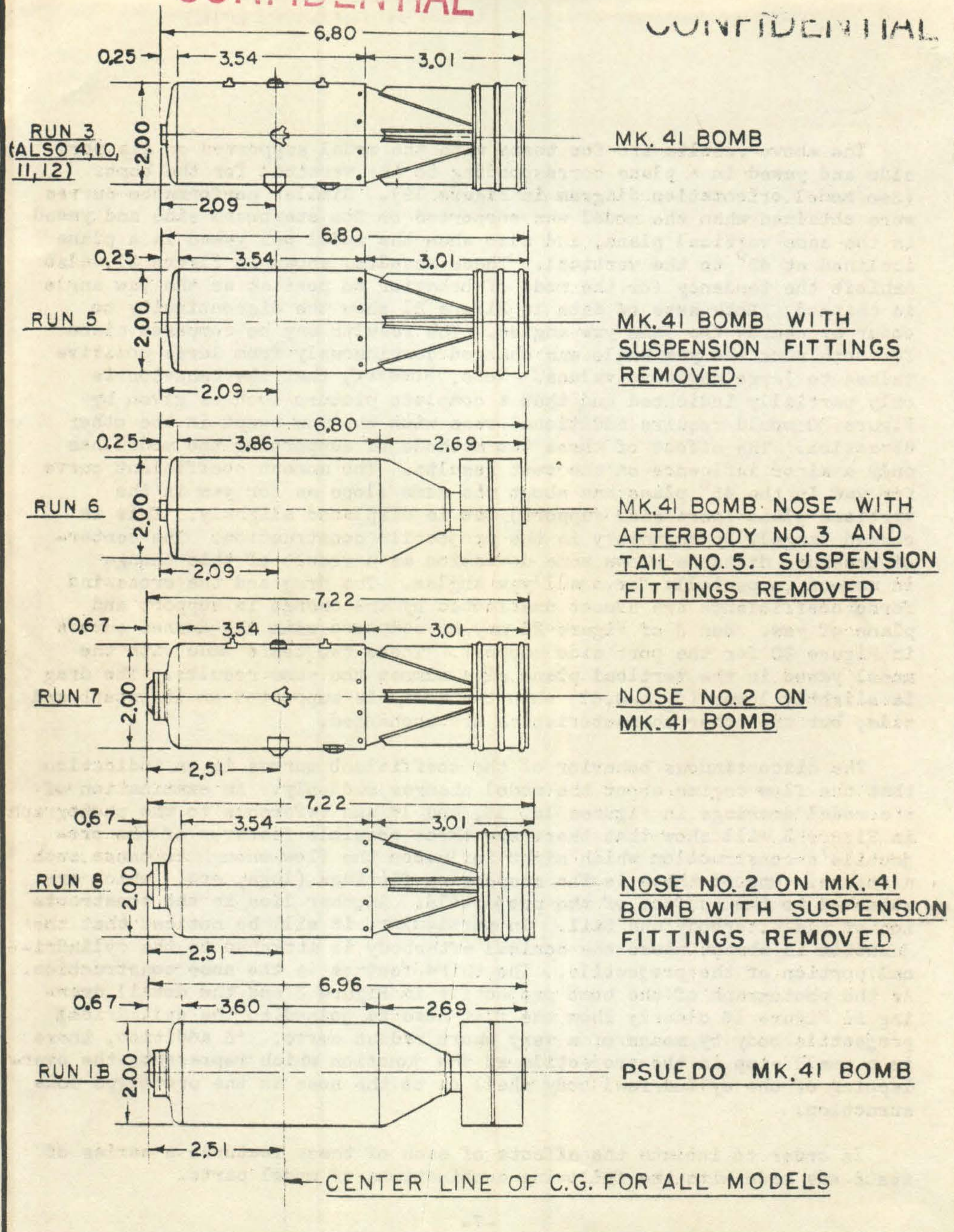

HYDRAULIC MACHINERY LABORATORY	CALIFORNIA INSTITUTE OF TECHNOLOGY	
DR J.W.C. 3-17-42	COMPARISON OF PROFILES OF	SCALE 3/8" = 1"
CH	2" DIA. MODEL COMBINATIONS	ND 14—683 L
AP		

195-L "ALBANENE"—K. & E. CO., N. Y.—REG. U.S. PAT. OFF.

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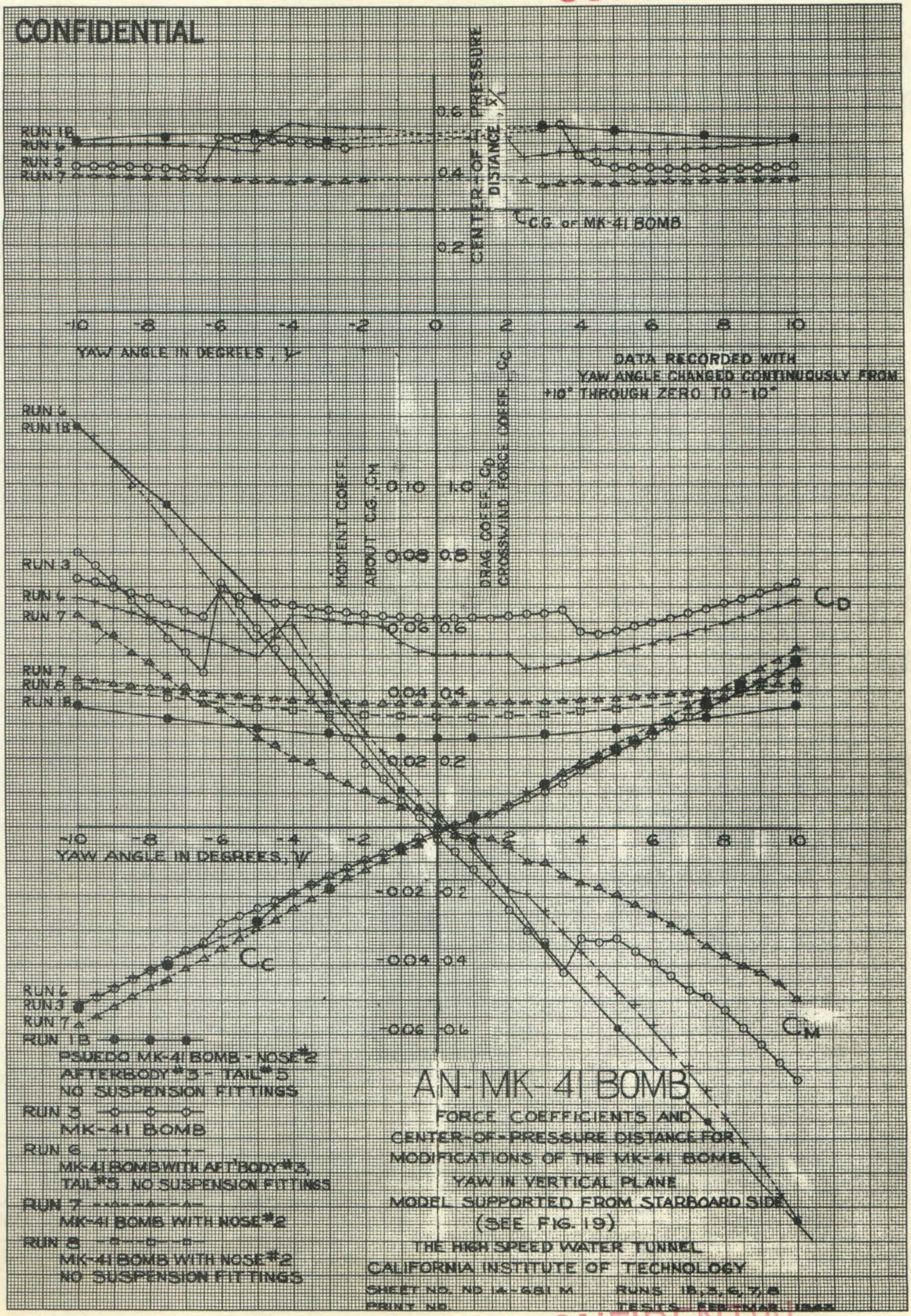
FIGURE 22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CENTER-OF-PRESSURE DISTANCE, X/L
0.6
0.4
0.2
RUN 1B
RUN 6
RUN 3
RUN 7
C.G. OF MK-41 BOMB
-10 -8 -6 -4 -2 0 2 4 6 8 10
YAW ANGLE IN DEGREES, ψ
DATA RECORDED WITH
YAW ANGLE CHANGED CONTINUOUSLY FROM
+10° THROUGH ZERO TO -10°
MOMENT COEFF. ABOUT C.G. C_M
DRAG COEFF. C_D
CROSSWIND FORCE COEFF. C_C
0.10 1.0
0.08 0.8
0.06 0.6
0.04 0.4
0.02 0.2
-0.02 -0.2
-0.04 -0.4
-0.06 -0.6
RUN 6
RUN 1B
RUN 3
RUN 6
RUN 7
RUN 7
RUN 8
RUN 8
C_D
C_C
C_M
RUN 6
RUN 3
RUN 7
RUN 1B
PSUEDO MK-41 BOMB - NOSE #2
AFTERBODY #3 - TAIL #5
NO SUSPENSION FITTINGS
RUN 3
MK-41 BOMB
RUN 6
MK-41 BOMB WITH AFTBODY #3,
TAIL #5. NO SUSPENSION FITTINGS
RUN 7
MK-41 BOMB WITH NOSE #2
RUN 8
MK-41 BOMB WITH NOSE #2
NO SUSPENSION FITTINGS
AN-MK-41 BOMB
FORCE COEFFICIENTS AND
CENTER-OF-PRESSURE DISTANCE FOR
MODIFICATIONS OF THE MK-41 BOMB
YAW IN VERTICAL PLANE
MODEL SUPPORTED FROM STARBOARD SIDE
(SEE FIG. 19)
THE HIGH SPEED WATER TUNNEL
CALIFORNIA INSTITUTE OF TECHNOLOGY
SHEET NO. ND 14-681 M
PRINT NO.
RUNS 1B, 3, 6, 7, 8
TESTS FEB-MAR 1945

FIG. 23

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1. Run 5 - All suspension lugs and fittings were removed from the Mk. 41 Bomb.

2. Run 6 - The Mk. 41 Tail and afterbody were replaced by a laboratory ring type tail and another afterbody and the suspension lugs and fittings removed. (Afterbody No. 3 and Tail No. 5). Photographs of this assembly are shown in Figures 11 and 12.

3. Run 7 - The Mk. 41 nose was replaced by a nose whose profile was faired smoothly into the body section profile with a larger radius curve (Nose No. 2). Photographs of this assembly are shown in Figures 13 and 14.

4. Run 8 - The same combination as No. 3, Run No. 7 was retested with the suspension fittings removed.

5. Run 1B - The Mk. 41 nose on combination No. 2 was replaced by the laboratory Nose No. 2, making a completely pseudo Mk. 41.

Profiles of each of these five combinations are shown compared with the regular Mk. 41 profile in Figure 22. Nose No. 2, afterbody No. 3 and tail No. 5 are similar in shape to those used on the mousetrap ammunition ASPC-CIT- lot O.

The results of the series of tests are shown on Figure 23 compared with those of Run 3 for the regular Mk. 41 Bomb. Some of the combinations do not have the same length as the regular Mk. 41. In calculating values of $\bar{x}/L$ the location of the center-of-gravity is assumed to be at the hydrostatic fuse centerline and the length, L, is taken as6.80" (the length of the 2" diameter model of the Mk. 41) for all combinations. This procedure makes the $\bar{x}/L$ values shown directly comparable.

The data for the Mk. 41 Bomb with the suspension fittings removed are not plotted since this modification resulted in no differance in behavior from that already observed with the fittings attached. As will be seen this interesting result is indirectly caused by the sharp curvature of the nose and the step in the profile where the nose joins the body section.

Run 6 shows the performance of combination No. 2. When the results of run 6 are compared with those of run 3 it is seen that the drag is reduced for all yaw angles and that $\bar{x}/L$ is increased from 0.43 to 0.50 for large yaw angles. For small yaw angles $\bar{x}/L$ in not changed appreciably. The curves also exhibit an abrupt discontinuity at both a positive and a negative yaw angle.

The curve labeled run 7 for the profile with the modified nose No. 2 shows an entirely different type of performance. None of the curves show the discontinuities observed for the other projectiles. In addition, the

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drag at zero yaw angles is reduced from 0.61 to 0.36 which causes a 30% increase in the terminal velocity of the bomb. The lack of any discontinuity in performance leaves $\bar{x}/L$ at a constant value for the entire yaw range. However, $\bar{x}/L$ is reduced in magnitude to 0.39, which reduces the stability somewhat. These very significant effects are the direct result of the change in nose shape and it is of interest to inquire how the effects arise.

As has been emphasized nose No. 2 forms a smooth and continuous profile at the junction with the body section. Thus, the features of the Mk. 41 nose which would contribute to disturbance and separation of the flow are modified. From an examination of the bomb profiles and the test results it is concluded that the flow around the Mk. 41 nose must separate where the nose joins the cylindrical body, and that it is a sudden change in the separation phenomena as the yaw angle is varied through the critical zone shown in Figure 20, that causes the discontinuities in performance curves. It is also probable that the separation is materially reduced if not eliminated when the modified nose is used. Evidence of this separation is shown in drawings of the observed flow patterns about the Mk. 41 Bomb with the regular and the modified noses. Figures 24 and 25 show these patterns for the two modifications both at zero yaw angle. These drawings were made from observations of the fluid motion around the model in the polarized light flume.(1) The fluid in the flume has asymmetrical physical and optical properties which permit observation of the flow lines when viewed through polarizing plates. The pictures are for flow velocities below the range of the water tunnel experiments and the patterns can be considered as only qualitative. However, they do illistrate the fundamental differences caused by the two noses. Figure 24 for the regular Mk. 41 nose shows how the flow fails to follow the profile of the bomb, and how it tends to jump clear or "separate" at the junction between the nose and cylindrical body section. It also shows how the main flow is pushed away from the bomb by the high velocity sheet of separating fluid. Inside this fast moving sheet, close to the body, is a zone of slow moving eddying fluid. This "stagnate" layer envelopes the forward portion of the body and in fact influences the flow back to the afterbody. The size of the eddying zone is an indication of large energy loss and is one cause of the high drag for this projectile. It is interesting to note that the forward and center suspension fittings are entirely within the eddying zone. This is important since it helps explain why the removal of the suspension fittings caused no noticable change in the performance of the projectile. Since the fittings only influence fluid that is already disturbed, they do not contribute materially to the forces acting on the bomb.

Figure 25, which is a diagram of the flow lines for the bomb with nose No. 2, shows a reduced tendency for the fluid to separate. The flow clings closer to the body profile and the sheet of fluid deflected at the nose disturbs the main flow for only a short distance from the body. There is a zone of slow moving eddying fluid but its influence is limited to a small area close to the projectile's nose. In this case, the suspension fittings extend through the thinner zone of disturbed fluid into the high

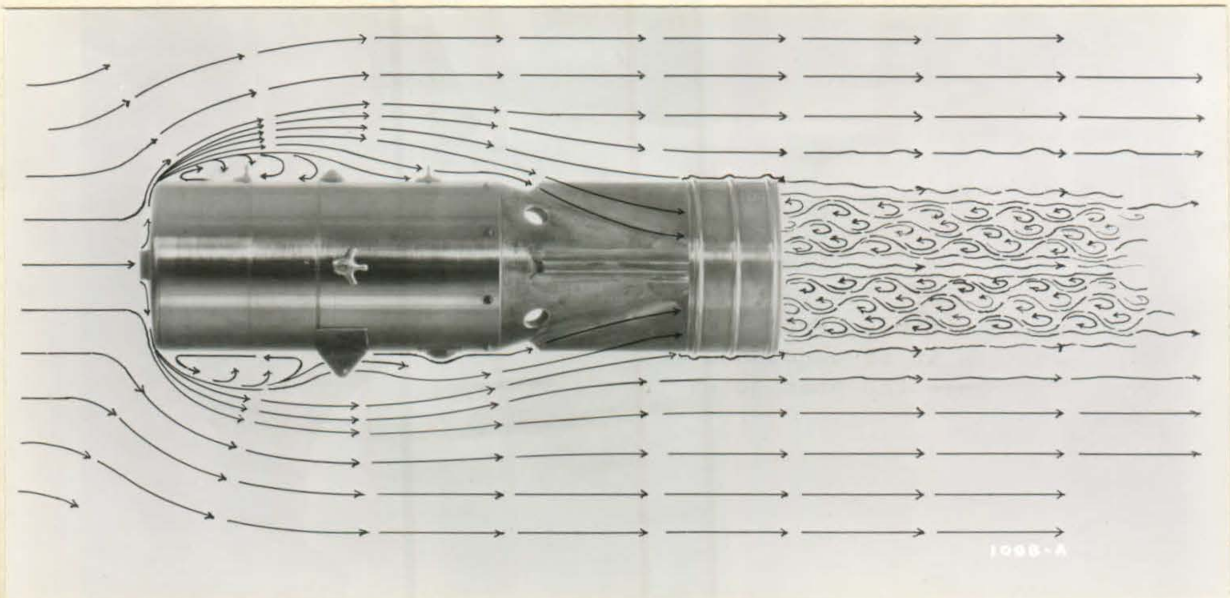


Figure 24. Flow Pattern around Mk. 41 Bomb for zero Yaw Angle. This drawing is based on observations of the actual flow.

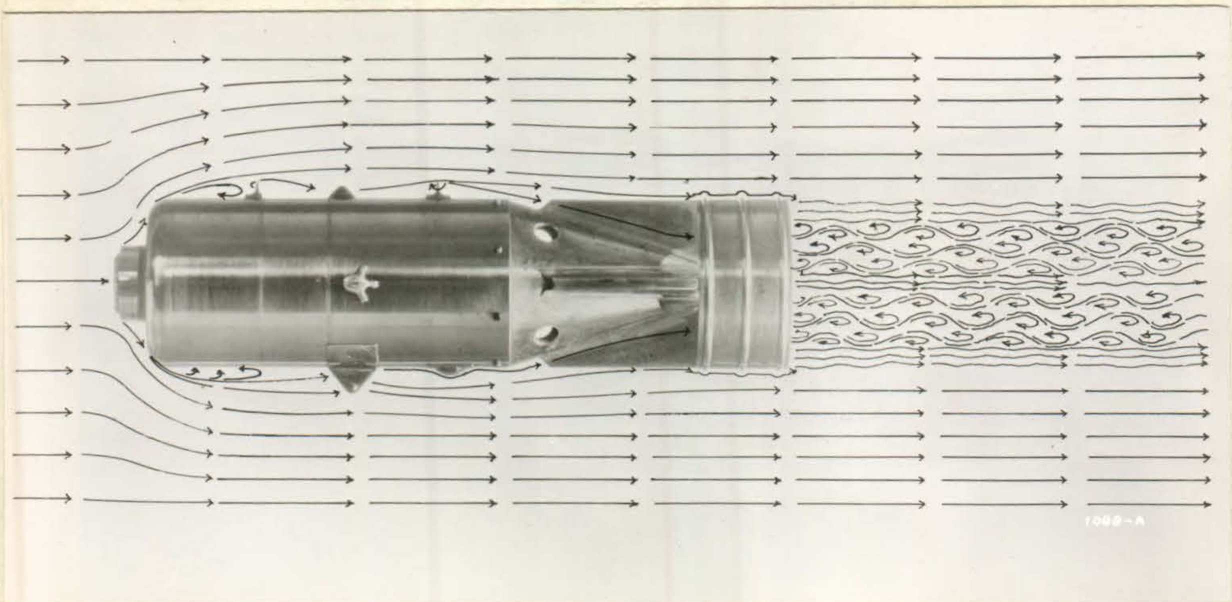


Figure 25. Flow Pattern around Mk. 41 Bomb with nose replaced by laboratory Nose No. 2. Zero Yaw Angle. This drawing is based on observations of the actual flow.

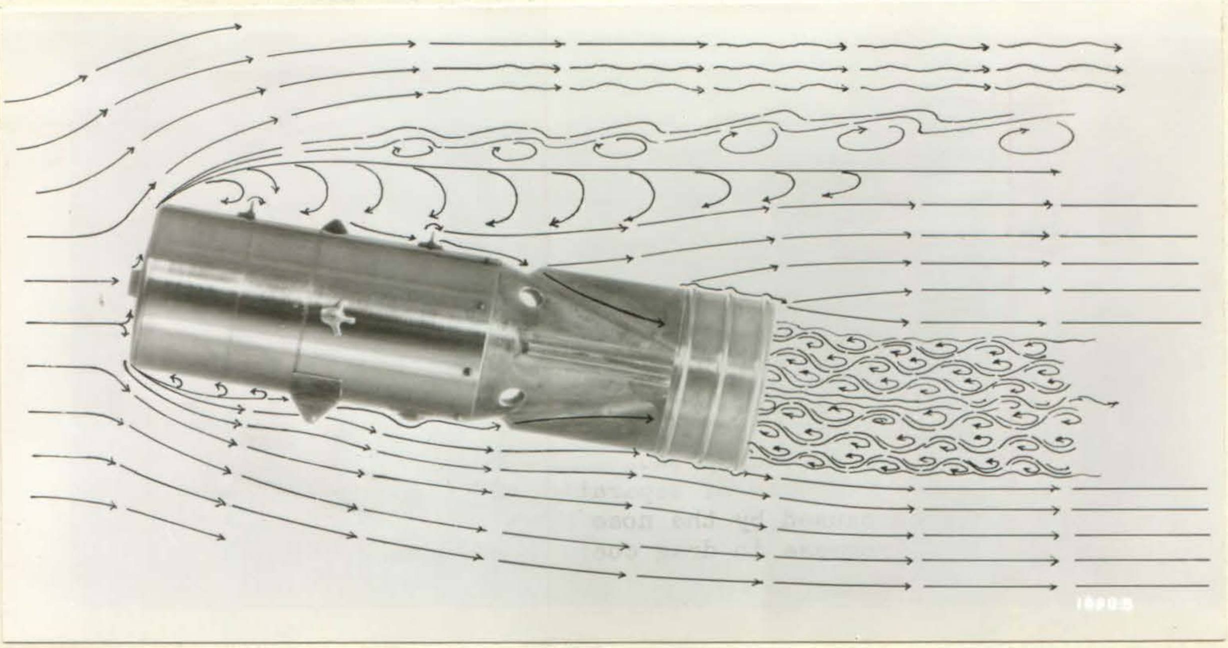


Figure 26. Flow Pattern around Mk. 41 Bomb in a yawed position. This drawing is based on observations of the actual flow.

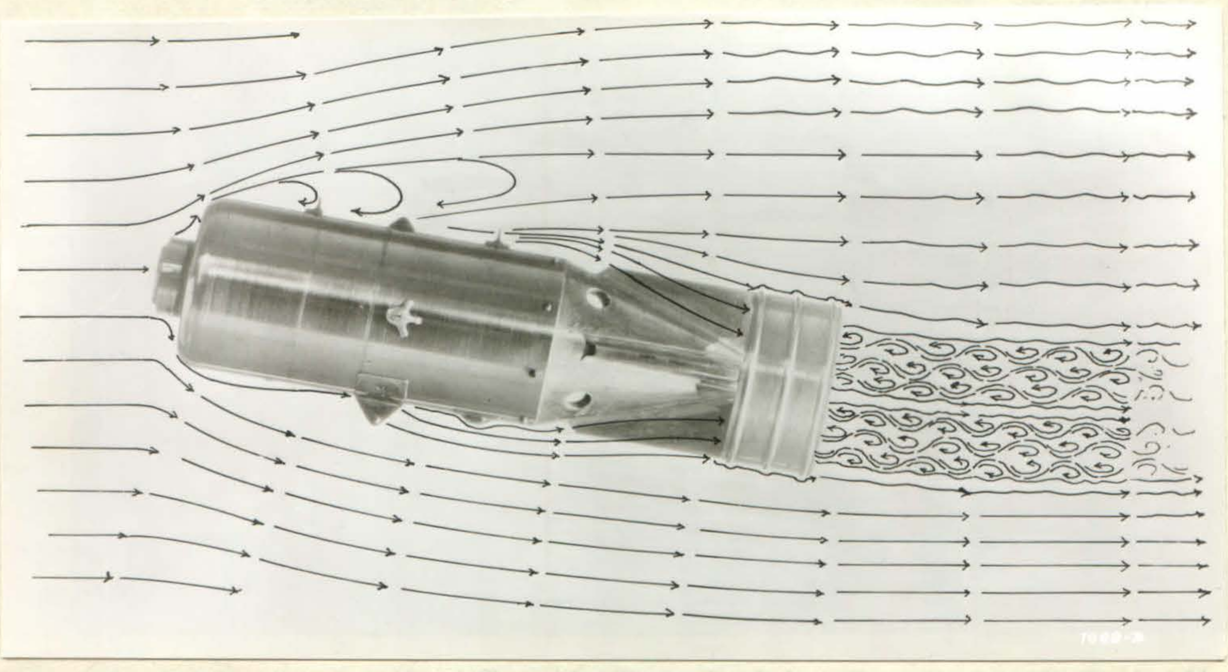


Figure 27. Flow Pattern around Mk. 41 Bomb with nose replaced by laboratory Nose No. 2. Yawed Position. This drawing is based on observations of the actual flow.

velocity main flow. It must be expected that their effect on the main flow would contribute to the forces acting on the projectile, and that some difference in behavior would be observed if the fittings were removed. The curves of C_D for run 8 in figure 23 shows this to be true. The drag coefficient is reduced from 0.36 to 0.32 when the fittings are eliminated. C_M , C_C, and $\overline{x}/L$ values are not shown since they were unaffected by the change.

Figures 26 and 27 show the flow patterns for the same two bombs at an angle of yaw. The flow around the nose of the regular Mk. 41 projectile again separates from the body at both top and bottom. At the top large eddying system sweeps back from the nose forcing the main flow away from the body. Below the model, the disturbed zone is much reduced over that shown in Figure 24. The flow pattern for nose No. 2, which appears on Figure 27, also shows rather severe separation at the top of the bomb, There is less disturbance to the main flow, however, as shown by the smaller zone of eddies extending back from the nose. Beneath the model there is very little evidence of separation for this nose. The relatively large disturbance caused by the nose of the regular Mk. 41 may account for the more rapid increase in drag coefficient with angle of yaw shown in Figure 23.

It should be noted that nose No. 2 is similar in shape to the nose used on the mousetrap bomb and that it differs only slightly from the regular Mk. 41 nose. Since the mousetrap is also designed for entry into the water after a flight in the air it is probable that nose No. 2 will work satisfactorily on the Mk. 41 bomb. Standard fuses can be used with nose No. 2, although it is not known if it will satisfy other design requirements.

The fifth combination of model parts, the "pseudo" Mk. 41 Bomb, which is made up with nose No. 2, afterbody No. 3, and tail No. 5, has the behavior shown by the curves of Run 18 on Figure 23. This model also lacks discontinuities in its performance curves. The drag, $C_D = 0.26$, is lower than for any other combination tested. In addition, the $\overline{x}/L$ values at large yaw angles are greater than for the other combinations, while in the range near zero yaw the $\overline{x}/L$ values compare favorably with the C.P distances for runs 3 and 6. Both run 18 and run 6 show some improvement in stability when afterbody No. 3 and tail No. 5 are used. This important effect is probably the result of more fluid passing through the tail and acting on the fins and shroud.

6. Test Results - Discussion of Projectile Behavior as Interpreted from Performance Curves.

The high drag and the discontinuity in the performance for this projectile are undesriable. The over-lap of angles at which the discontinuity occurs represents a zone of uncertainty where the behavior of the projectile will depend upon the sign of the yawing and the magnitude of the disturbance encountered in free flight. This discontinuous behavior is probably affected by Reynolds number. The tests described in Section 5 were all conducted with a tunnel velocity of 31 feet per second, which for a 2" diameter model gives a Reynolds number of 410,000. (The diameter is the length parameter in this calculation). The actual conditions which the prototype will encounter differ from this. The terminal velocity for the bomb under water will be approximately 15.0 feet per second, assuming the drag coefficient to be 0.64. For the 15" prototype this gives a Reynolds number of 1,500,000. There is a possibility that even greater Reynolds numbers will be encountered for free flight of the projectile in air, where the maximum velocity will depend upon the altitude at which the bomb is released, and the speed of the plane at the time of release. For release at an altitude of 500 feet from a plane traveling at a speed of 300 miles per hour the velocity will be approximately 475 feet per second when the projectile hits the water. This gives a Reynolds number of over 3,700,000. It is clear that the effect of the velocity may be important. For this reason additional tests were made at tunnel velocities of 15 feet per second ($R = 200,000$) and 35 feet per second ($R = 465,000$) to see if there was any marked change in the behavior.

Figure 28 shows a comparison of the performance curves obtained for tunnel tests at the three velocities of 15, 31, and 35 feet per second. First, it is observed that curves of run 11 for 15 feet per second are very different from those for the higher speeds. The drag coefficient at zero yaw is 0.67 as against 0.61 at 31 feet per second, (run 3) and the discontinuities observed for the high speed run are totally absent at the lower speed within the plus or minus 10° yaw angle range covered. The fact that the character of the performance curves changed between 15 feet per second, or $R = 200,000$, and 31 feet per second, or $R = 410,000$, is important since it indicates that model tests made at very low values of Reynolds number may not always give results which are accurate for the prototype.

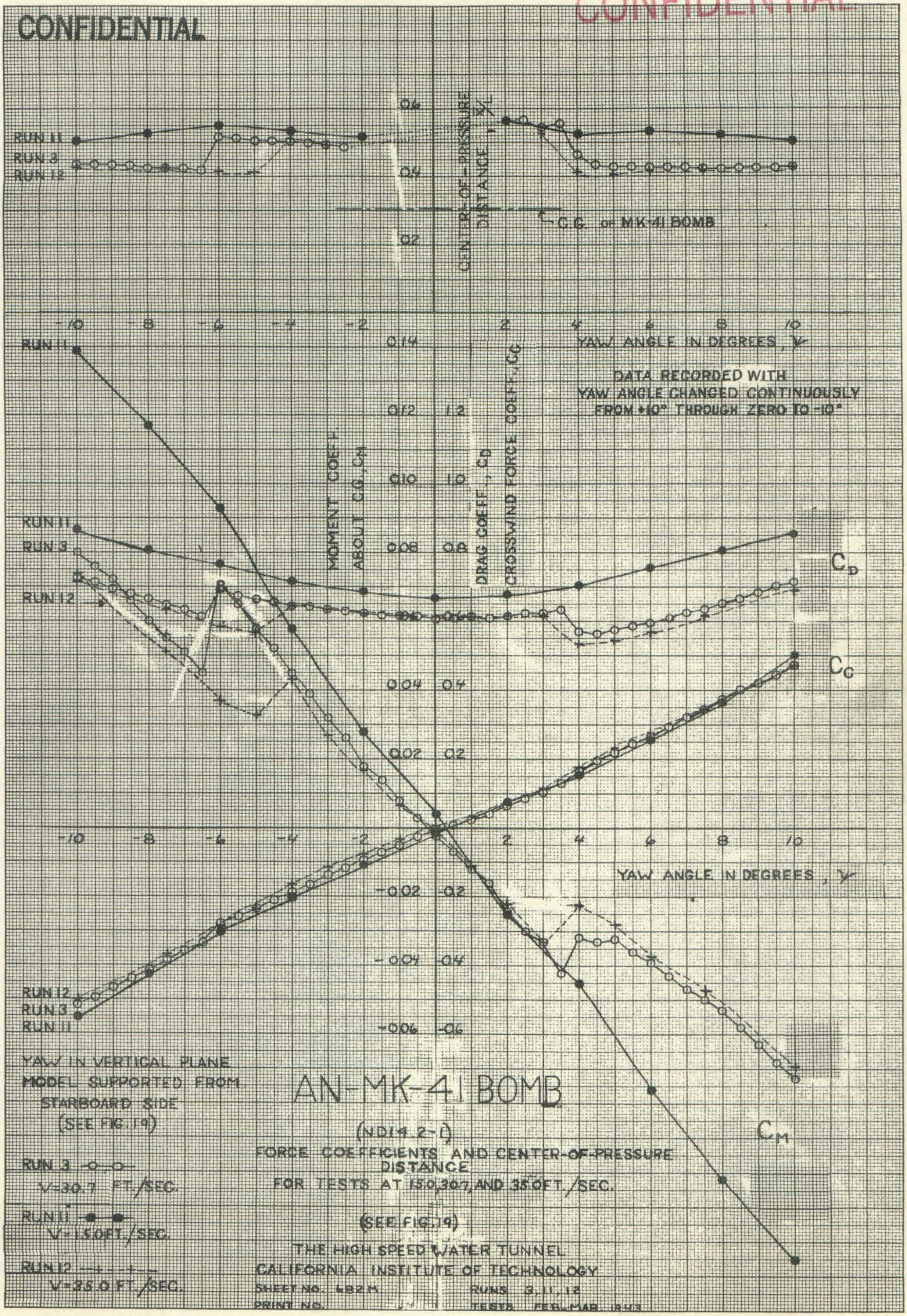
On the other hand, run 12 at 35 feet per second, or $R = 465,000$, shows only minor differences over the performance at 31 feet per second. The drag is the same near zero yaw and is a small amount lower for large yaw angles. The discontinuities exist, and while the jump in the curves occurs at a smaller negative yaw angle than for $V = 31$ feet per second, it occurs at the same positive angle. It is not felt that this difference observed for negative yawing is significant. The center-of-pressure distance values are very nearly the same for both velocities. It appears that the tests at 31 and 35 feet per second are above the point where marked Reynolds number effects will be observed. Consequently, it is thought that these test results represent closely the true behavior of the actual projectile. Futhermore, it is expected that the results will hold for flight in either water or air since the prototype Reynolds number in water is only three times the test value, and in air is only about eight times the test value (assuming R in air $= 3,700,000$ as calculated above.)

Referring again to Figure 20 it will be noted that the center-of-gravity is located at a distance of 0.31 L back of the projectile nose. Thus, in spite of the fact that the sudden changes in the characteristic curves give uncertainty in the behavior and result in less stability at large yaw angles than at angles near zero the projectile indicates definite static stability over the entire yaw range. Unless these changes in behavior with yaw angle introduce undesirable dynamic effects it may be that the high drag is the most serious consequence of the characteristics.

The above discussion of the behavior of the bomb considers only the static stability. The dynamic stability, the discussion of the mode of motion which follows any disturbance, will depend also upon the so-called "apparent mass" effects which arise when a body moving in a fluid is accelerated in any direction. When the fluid is air the apparent masses are small relative to the mass of the bomb and they may be neglected. However, in water the apparent masses are considerably larger and may not be negligible. It is clear, therefore, that the behavior will be different in air than in water. For this bomb, Figure 20 shows the distance between the C.G and C.P. to be approximately 22% of the over-all length at zero yaw and 12% of the over-all length at large yaw angles. This should be an adequate margin for stability of the projectile in either air or water. If the regular nose is replaced by the laboratory nose No. 2, Figure 23 shows that the difference between C.G. and C.P. locations is approximately 8% of the bomb length for all yaw angles. This may be sufficient for dynamic stability. The curves of Figure 23 also show that at large yaw angles, beyond the zone of discontinuities, ring tail No. 5 and afterbody No. 3 cause greater moments and greater $\bar{x}/L$ values than the regular Mk. 41 tail and afterbody. This improvement in stability is obtained when the modified tail and afterbody is used with either the regular Mk. 41 nose or nose No. 2 from the laboratory stock. For yaw angles near zero, however, the center-of-pressure distance is not changed appreciably.

The projectile's behavior was also measured with the pressure reduced enough to cause some cavitation at the junction between the nose and the cylindrical body section. The visible cavitating zone extended for a distance of approximately two thirds a model diameter aft from the junction. This test, made with a 35 feet per second velocity in the water tunnel working section, gave results similar to those of run 12 in Figure 28. The drag was increased a very small amount over run 12 and the zone of high C_D, C_M, and $\bar{x}/L$ extended over a larger range of yaw angles. Otherwise the performance curves were identical with those fpr run 12. The fact that the cavitation affected the behavior so slightly is an indication of how severely the flow around the bomb is disturbed by the separation at the nose for non-cavitating conditions.

For the Mk. 41 bomb the pressure at which marked cavitation appears was found to be approximately $2.9 \rho V^2/2$, where ρ is the density of the fluid, V is the relative velocity of the flow past the bomb, and the pressure is measured above the vapor pressure of the water. This means that the bomb will not cavitate if it travels no faster than its terminal velocity of 15.0 feet per second. However, at entrance the velocity will exceed this value considerably and cavitation will probably occur. For



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RUN 11
RUN 3
RUN 12
CENTER-OF-PRESSURE DISTANCE, X/L
C.G. OF MK-41 BOMB
YAW ANGLE IN DEGREES, ψ
DATA RECORDED WITH YAW ANGLE CHANGED CONTINUOUSLY FROM +10° THROUGH ZERO TO -10°
MOMENT COEFF. ABOUT C.G., C_M
DRAG COEFF., C_D
CROSSWIND FORCE COEFF., C_C
C_D
C_C
C_M
YAW IN VERTICAL PLANE
MODEL SUPPORTED FROM STARBOARD SIDE
(SEE FIG. 19)
RUN 3 -o-o-
V=30.7 FT./SEC.
RUN 11 -●-●-
V=15.0 FT./SEC.
RUN 12 -+-+-
V=35.0 FT./SEC.
AN-MK-41 BOMB
(NDI4.2-1)
FORCE COEFFICIENTS AND CENTER-OF-PRESSURE DISTANCE
FOR TESTS AT 15.0, 30.7, AND 35.0 FT./SEC.
(SEE FIG. 19)
THE HIGH SPEED WATER TUNNEL
CALIFORNIA INSTITUTE OF TECHNOLOGY
SHEET NO. 482M
PRINT NO.
RUNS 3, 11, 12
TESTS FEB.-MAR. 1943

FIG. 28

instance, with a submergence of 5 feet the nose will cavitate when the velocity of the bomb is about 29 feet per sec.

7. Summary.

1. The characteristics of the AN-Mk. 41 Bomb as determined from tests are represented in the curves of Figure 20. These curves show that at zero yaw angle, the drag coefficient is 0.64 and that the center-of-pressure distance is 0.52. The center-of-pressure is aft of the center-of-gravity by about 0.22 times the overall length. These curves also show that a sudden decrease in drag, moment, and center-of-pressure distance occurs between yaw angles of 2 and 6 degrees. The zone over which these discontinuities occur depends upon whether the yaw angle is increasing or decreasing in absolute magnitude and upon the velocity or Reynolds number. Run No. 11,(Figure 28) made at a Reynolds number of 200,000 shows no discontinuities in the curves while tests at a Reynolds number of 410,000 gave the discontinuities shown in Figure 20.

The range of yaw angles over which the discontinuities occur represents a zone of uncertainty in the behavior of the bomb. Near zero yaw the center-of-pressure (C.P.) is aft of the C.G. a distance of approximately 0.22 times the overall length indicating that in this region the bomb is very stable statically, and very probably also dynamically. The sudden decrease in moment at the discontinuity point tends to reduce the stability but this reduction is prboably not sufficient to make the bomb unstable.

2. The terminal velocity of the bomb in water is about 15 feet per second, which gives a Reynolds number of only about three times that for the water tunnel tests shown in Figure 20. Therefore, it is expected that the test results will describe accurately the behavior of the bomb in water. In air the velocity and resulting Reynolds number will be about eight times the test values (assume bomb released 500 feet above water from plane traveling at a speed of 300 mph.) This is still within the range where the test results should apply with reasonable accuracy.

3. By rounding the nose of the bomb slightly it is possible to reduce the drag materially, thus increasing the terminal velocity, and to eliminate completely the discontinuities in the characteristic curves. As run 7 on Figure 23 indicates the use of nose No. 2 shown in Figure 18 in place of the regular nose of the Mk. 41 bomb reduced the drag coefficient to 0.36, thus giving an increase in terminal velocity of about 30%. However, at the same time the moment and center-of-pressure distance were reduced giving a distance of the C.P. aft of the C.G. of 0.08 times the length. This gives substantial static stability and may possibly give adequate dynamic stablity.

It is probable that the Mk. 41 Bomb with nose No. 2 would enter the water surface satisfactorily since this nose was used on the mousetrap projectile under similar operating conditions. However, it is not known whether this nose shape would satisfy other design requirements.

4. Some decrease in drag and increase in stability can be obtained by modifying the tail and afterbody of the Mk. 41 Bomb. Tests of a bomb model with afterbody No. 3 and tail No. 5 shown in Figure 18 gave a reduced drag for all yaw angles and an increase in the center-of-pressure distance for angles of yaw greater than 6 degrees. (Figure 23, run No. 6). For yaw angles up to 6 degrees the C.P. distance was not changed appreciably by the modified tail and afterbody.

5. The best model combination tested used a mousetrap nose, afterbody and tail. (nose No. 2, afterbody No. 3, and tail No. 5). For this combination the stability is about the same as for the Mk. 41 bomb up to yaw angles of 5 degrees and for larger angles the stability is greater than for the Mk. 41 bomb as may be seen from the curves for run 1B in Figure 23. Also, the drag coefficient is reduced from 0.61 to the low value of 0.26. This means that the terminal velocity of the bomb in water is increased from 15 to about 23 feet per second.

6. Tests showed that the suspension lugs and other fittings do not affect the drag or other forces on the Mk. 41 bomb because the fittings apparently lie within the fluid that is disturbed by the flat nose. With nose No. 2 the disturbed fluid is reduced in thickness so the fittings extend through it into the high velocity flow. In this case, removing the fittings reduced the drag coefficient by about 8 percent without changing the other force coefficients.

7. Tests on the Mk. 41 bomb showed that with slight cavitation at the junction of the nose and body section the drag was increased a small amount while the other forces remained the same as without cavitation. The fact that cavitation produces so little change indicates the severe nature of the disturbance caused by separation at the nose even before cavitation occurs.

References:

(1) For complete description see "The High Speed Water Tunnel at the California Institute of Technology", by R. T. Knapp, V. A. Vanoni, and J. W. Daily, NML Rep. No. ND-1, June 29, 1942.

(2) "Aerodynamic Theory" edited by W. F. Durand, Vol. IV Div. J, Chapter I, Julius Springer Berlin, 1934, pp-7.

4. Some decrease in drag and increase in stability can be obtained by modifying the tail and afterbody of the Mk. 41 bomb. Tests of a bomb model with afterbody No. 3 and tail No. 8 shown in Figure 22 gave a reduced drag for all yaw angles and an increase in the center-of-pressure distance for angles of yaw greater than 6 degrees. (Figure 23, run No. 5). For yaw angles up to 6 degrees the C.P. distance was not changed appreciably by the modified tail and afterbody.

5. The best model combination tested used a cavitator nose, afterbody and tail, (nose No. 2, afterbody No. 3, and tail No. 8). For this combination the stability is about the same as for the Mk. 41 bomb up to yaw angles of 6 degrees and for larger angles the stability is greater than for the Mk. 41 bomb as may be seen from the curves for run 13 in Figure 23. Also, the drag coefficient is reduced from 0.31 to the low value of 0.20. This means that the terminal velocity of the bomb in water is increased from 15 to about 22 feet per second.

6. Tests showed that the suspension lugs and other fittings do not affect the drag or other forces on the Mk. 41 bomb because the fittings apparently lie within the fluid which is disturbed by the flat nose. With nose No. 2 the disturbed field is reduced in thickness so the fittings extend through it into the high velocity flow. In this case, removing the fittings reduced the drag coefficient by about 5 percent without changing the other force coefficients.

7. Tests on the Mk. 41 bomb showed that with slight cavitation at the junction of the nose and body section the drag was increased a small amount while the other forces remained the same as without cavitation. The fact that cavitation produces so little change indicates the severe nature of the disturbance caused by separation at the nose even before cavitation occurs.

References:

(1) For complete description see "The High Speed Water Tunnel at the California Institute of Technology", by R. T. Knapp, [illegible], and J. W. Daily, NDRC Rep. No. ND-[illegible], June [illegible], 1942.

(2) "Aerodynamic Theory" edited by W. F. Durand, Vol. IV Div. J, Chapter [illegible], Julius Springer Berlin, 1935, p. [illegible].